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Brimrose Corporation of America reports the successful completion of the SBIR Phase I research in low-threshold intensity optical bistable devices using photorefractive nonlinearity. A thin photorefractive film optical bistable device was proposed in the Phase I proposal. The feasibility of this device was theoretically investigated. The theoretical feasibility study formulates the materials requirements in such a kind of configuration for Phase II research. In addition, we have proposed and investigated another configuration of optical bistable devices that do not require advanced photorefractive materials, namely, the self-pumped phase conjugator. We have successfully demonstrated a low-threshold optical bistable operation in a KNSBN:Cu crystal. To the best of our knowledge, the threshold of mW/cm^2 is the lowest of its kind to be achieved so far.

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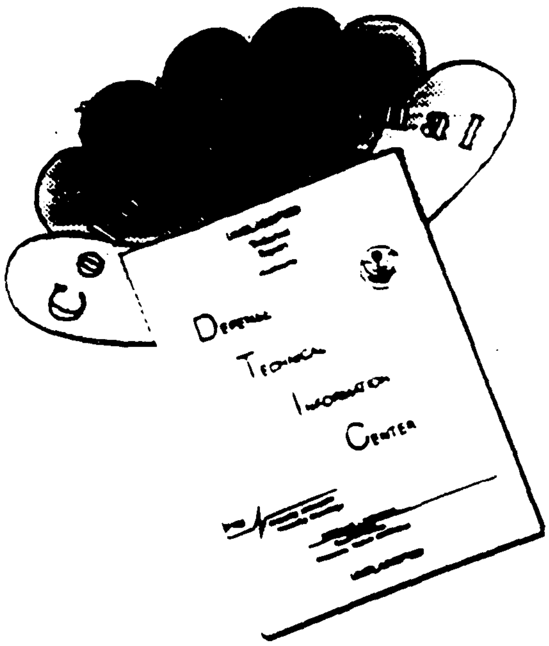

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A NOVEL OPTIC BISTABLE DEVICE WITH VERY LOW THRESHOLD INTENSITY USING PHOTOREFRACTIVE FILMS

(SBIR Phase I Contract)

Sponsored By: US AIR FORCE

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A NOVEL OPTIC BISTABLE DEVICE WITH VERY LOW THRESHOLD INTENSITY USING PHOTOREFRACTIVE FILM

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A NOVEL OPTIC BISTABLE DEVICE WITH VERY LOW THRESHOLD INTENSITY USING PHOTOREFRACTIVE FILM

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EXECUTIVE SUMMARY

Brimrose Corporation of America reports the successful completion of the SBIR Phase I research in low-threshold intensity optical bistable devices using photorefractive nonlinearity. A thin photorefractive film optical bistable device was proposed in the Phase I proposal. The feasibility of this device was theoretically investigated. The theoretical feasibility study formulates the materials requirements in such a kind of configuration for Phase II research. In addition, we have proposed and investigated another configuration of optical bistable devices that do not require advanced photorefractive materials, namely, the self-pumped phase conjugator. We have successfully demonstrated a low-threshold optical bistable operation in a KNSBN:Cu crystal. To the best of our knowledge, the threshold of 650 mW/cm^2 is the lowest of its kind to be achieved so far.

In summary, the Phase I research achievements are:

1) Theoretically demonstrated the feasibility of the thin film photorefractive optical bistable device. In addition, a technical paper is under preparation for publication in *Opt. Lett.* [2].

2) The theoretical work has also generated necessary guidelines and goals for the Phase II materials development for the implementation of the thin film device.

3) A simple, bulk version of the low threshold optical bistable device was experimentally demonstrated. The threshold for the bistable operation is the lowest of its kind demonstrated so far. The results will be submitted for publication in *Photonics Lett.* [3].

In the Phase II program, emphasis will be placed in the following areas:

Device Optimization. Based upon the results from Phase I, further work for optimal parameters of the bistable device using self-pumped phase conjugation and two wave mixing in bulk crystals. The device will also be implemented in Brimrose's II-VI semiconductor materials which have faster response time and operate in IR wavelengths. In addtion, the proposed thin film device will also be further optimized for achieving a better performance.

Photorefractive Materials Growth. The on-going research of photorefrative materials growth in the phase II work will be aimed at increasing the deep trap level concentration in photorefractive II-VI semiconductors which are preferred due to their fast response time and matched with the wavelengths of laser diodes.

There are anticipated **commercial spin-offs** during the Phase II program. Novel optical bistable devices and subsystems will be available for commercial sales for applications ranging from optical computing, high-density all-optical memory for video on demand, optical communications, etc.

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1.0 IDENTIFICATION OF THE SIGNIFICANCE OF OPPORTUNITY

1.1 INTRODUCTION

Lightwave provides a powerful means for optical communications and optical computing due to its intrinsic ultra high information bandwidth and its parallel processing and interconnection capability.

In an optical computer, if this parallelism of the processing elements and the interconnections were combined with high switching speeds, the result would yield staggering computational power. Since the gates are operated in parallel, the data throughput is the product of the number of gates N and their speeds. If it were possible to have $N=10^6$ optical gates operating with a switching time of 0.1 ns, the system could perform 10^{16} bit operations per second. This extremely high rate is approximately the same as that of the human brain and is orders of magnitude greater than the largest currently available electronic computer [4].

Constructing the National Information Superhighways (NIS) and establishing an advanced National Information Infrastructure (NII) are essential to our nation's economic growth, improving the quality of life and enhancing our international business competitiveness. The volume and type of data needed to be transported include multimedia, interactive video, medical imagery, defense and national security data, distribute industrial and military operation simulations, data band information sharing, etc. Due to the so-called electronic bottleneck, current computer networks simply can not handle the anticipated amount of traffic, even all backbones and data links are replaced with high speed fibers. One likely solution to this complex problem is to use an all-optical network by which the electronic bottlenecks are bypassed. One example of the near term application of this all-optic approach is a high-speed optical bridge/router which can be used to interconnect local area networks (LANs) and/or wide area networks (WANs) [5]. The building block of this optical bridge/router will be optical shift registers which can be constructed from all-optic flip-flops.

Any highly sophisticated digital optical system must contain a large number of interconnected basic units: switches, gates and memory elements (flip-flops). Bistable optical devices are essential components which can be used as optical gates and flip-flops.

1.2 OPTICAL BISTABLE DEVICES

Since the first experimental demonstration [6] of an internally driven, sodium vapor filled Fabry-Perot cavity acting as an optical bistable device, there has been an upsurge of experimental and theoretical activities in the field of optical bistability [7-12].

An ideal optical bistable device should have the following combined characteristics

1) Low optical threshold intensity;
2) All-optical operation;
3) Fast response time;
4) Operable under laser diode wavelengths (0.8 μm, 1.3 μm and 1.55 μm).

Two essential ingredients of optical bistability are nonlinearity and feedback. Feedback is usually provided by optical resonators such as Fabry-Perot cavities [6-9]. Nonlinearity is derived from nonlinear optical materials such as Kerr media, semiconductors, liquid crystals etc. However, the threshold intensities of these devices demonstrated are typically about 10^8 W/cm^2. In recent years, photorefractive nonlinear materials have been studied [10-11] due to their low threshold intensities.

The main objective of the present work is to research and develop all-optic bistable devices based on photorefractive material. These devices will have the potential to be operated with very low threshold powers. Also as preferred, the program will be tied to II-IV semiconductor photorefactive materials such as *ZnTe:V, CdTe:V, CdS, CdMnTe* etc. In comparison to dielectric materials, they are advantageous for near infrared wavelength operation and fast time constant. Brimrose is the leader in research and commercially production of these materials [12-15].

As a result of the present program, two types of optic bistable devices have been developed in which photorefractive as the nonlinear mechanism was used. The first device shown in Figure 1, consists of a thin film of photorefractive material sandwiched between two semi-infinite dielectrics. The feedback is derived multiple reflections from both boundary interfaces and nonlinearity is derived from two-wave coupling experienced by the transmitted wave and partially reflected wave of the photorefractive thin film. The second device, shown in Figure 2, consists of a piece of photorefractive crystal, such as a KNSBN:Cu crystal used in our experiment. Its feedback is derived from beam loop formed by two internal reflections at two adjacent crystal faces.

The detailed theoretical work and experimental results will be presented in Chapters 2 and 3. Table 2 is a partial list of previously demonstrated optical bistable devices with good representation for reviewing purpose.

Table I. List of Demonstrated Optical Bistable Devices

Name	Time	Nonlinear Material	Feedback	Type	Threshold Intensity
H.M.Gibbsat al [6]	1976	sodium vapor	Fabry-Perot Cavity	Nonlinear dispersion	$10^8 W/cm^2$
D.A.B. Miller at al [9]	1979	Semiconductor InSb	Fabry-Perot Interferometer	Two-beam amplification	
G. P. Agrawalat al [10]	1981	Photo-refractive materials	Fabry-Perot Interfero-meter	Electro-optical modulation	$mw/\mu m^2$
Y.H.Ja [11]	1993	Photo-refractive optical fiber	Optical fiber ring resonator	Two-wave mixing	Theoretic-al demonstration
Smith[16]	1984	II-VI Semiconductors ZnS and ZnSe	Fabry-Perot Interference filter	All- Optical (Controlling Light with Light)	Pulsed laser source
Brimrose[1-2]	1993	Photo-refractive film	Thin Film Fabry-Perot	Two-wave Mixing	mW/cm^2
Brimrose[3]	1994	Photo-refractive crystal KNSBN:Cu	Crystal Internal Reflection	Four-wave Mixing Phase Conjugation	mW/mm^2

2.0 A NOVEL OPTIC BISTABLE DEVICE USING PHOTOREFRACTIVE FILMS

2.1 GEOMETRY OF THE PROPOSED BISTABLE DEVICE

The geometry of the proposed bistable device is shown in Figure 1. A thin film of photorefractive (PR) semiconductor *CdMnTe* is sandwiched between two semi-infinite dielectric materials, of which the cover is air and the substrate is *GaP* or *ZnTe*. The intuitive reason for proposing this device is to realize optical bistability. It posses all the proper ingredients namely, nonlinearity and feedback.

The input plane wave is incident from the cover side onto the cover-PR interface then is partially reflected (Br) and is partially transmitted. The transmitted wave C_- traverses the PR region then is partially reflected back into the PR semiconductor film (C_+) and partially transmitted (A_t). Due to the photorefractive nonlinearity, the waves C_+ and C_- experience two-wave coupling. This is the nonlinear mechanism of the proposed bistable device. In the meantime, the boundary conditions at the two interfaces must be satisfied, which provides the necessary feedback.

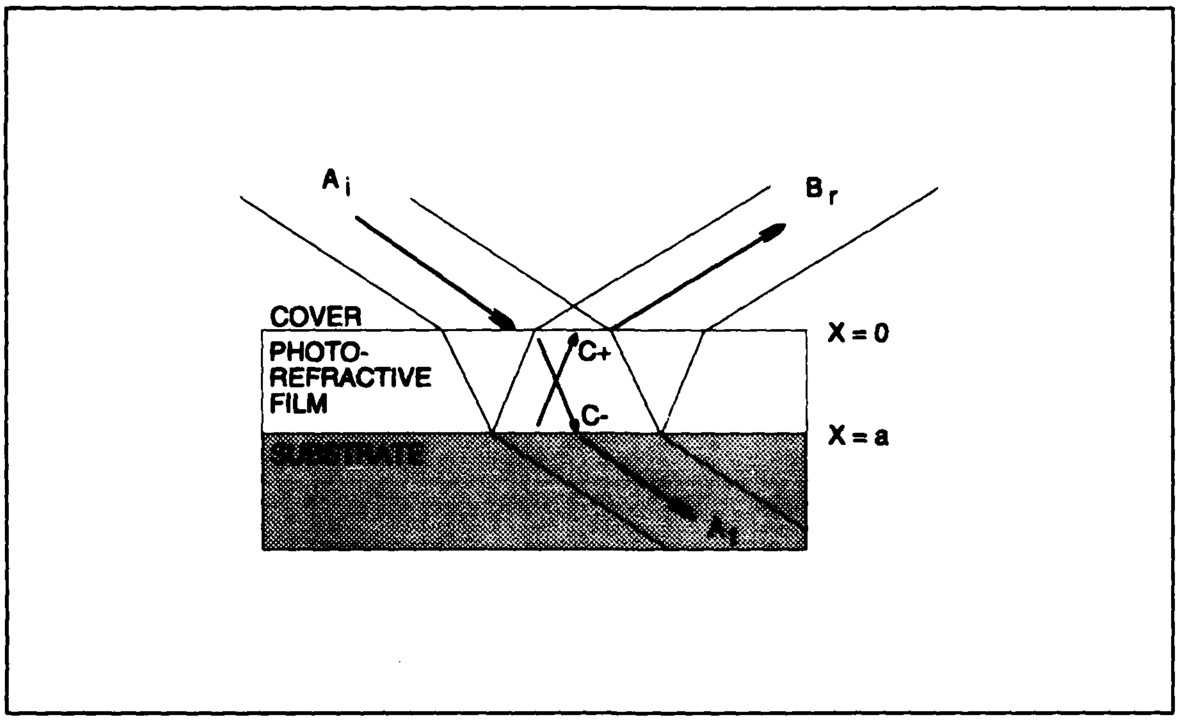

Figure 1 Geometry of a bistable device using photorefractive film.

2.2 DEVICE ANALYSIS

This analysis only treats transverse electric (TE) mode with the transverse electric field, $E_y(x)exp[-i(\omega t- \beta z)]$ governed by

$$[\frac{d^2}{dx^2}+(\omega^2\mu_0\varepsilon_0\varepsilon_{n}-\beta^2)]\ E_y(x)\ =0 \quad for \quad i = 1,\ 2,\ 3, \tag{1}$$

where the time and z-dependence $exp[-i(\omega t - \beta z)]$ has been assumed. The field associated with the incident and reflected waves in the cover, the upward and downward waves in the PR film and the transmitted wave in the substrate satisfy Eq.(1) and are given by the following expression:

$$E_{y1}= a_i\ [-i(\omega t-\beta z+k_{x1}x)]\ +\ b_r\ \exp\ [-i(\omega t-\beta z-k_{x1}x)]$$

$$for\ the\ cover\ region\ k_{x1}\ =\ \sqrt{\omega^2\mu_0\varepsilon_0\varepsilon_{r1}\ -\beta^2} \tag{2}$$

$$E_{y1}=c_-(x)\exp[-i(\omega t-\beta z+k_{x2}x)]+c_+(x)\exp[-i(\omega z-\beta z+k_{x2}x)] \tag{3}$$

$$for\ the\ film\ region\ with\ k_{x2}\ =\ \sqrt{\omega^2\mu_0\varepsilon_0\varepsilon_{r2}-\beta^2}$$

$$E_{y1}\ =\ a_t\exp\ [-i(\omega t-\beta z-k_{x3}(x+a))] \tag{4}$$

For the cover region with

$$k_{x3}=\sqrt{\omega^2\mu_0\varepsilon_0\varepsilon_{r3}-\beta^2}$$

The amplitudes of the incident wave, a_i, the reflected wave, b_r and the transmitted wave, a_t, are constants invariant in the x direction. Because of the photorefractive nature of the film, the amplitude of the upward and downward waves, c_- and c_+, vary with x and are coupled through two-wave mixing. For these two counter propagating waves, the coupled-wave equation describing the two-wave mixing process are as follows:

$$\frac{dc_+}{dx} = \gamma\frac{|c_-|^2 c_+}{|c_+|^2+|c_-|^2} - \frac{\alpha}{2}c_+ \tag{5}$$

$$\frac{dc_-}{dx} = \gamma^*\frac{|c_+|^2 c_-}{|c_+|^2+|c_-|^2} + \frac{\alpha}{2}c_- \tag{6}$$

Where γ is the two-wave mixing coupling coefficient and α is the intensity absorption coefficient. For simplicity, we will assume that the losses in the PR film are negligible. The complex differential equations can be separated into four real differential equations for the magnitude and phase of the two complex amplitudes as follows:

$$\frac{d|c_+|^2}{dx} = 2\gamma_R \frac{|c_-|^2|c_+|^2}{|c_+|^2+|c_-|^2} \tag{7}$$

$$\frac{d|c_-|^2}{dx} = 2\gamma_R \frac{|c_-|^2|c_+|^2}{|c_+|^2+|c_-|^2} \tag{8}$$

$$\frac{d\varphi_+}{dx} = \gamma_I \frac{|c_-|^2}{|c_+|^2+|c_-|^2} \tag{9}$$

$$\frac{d\varphi_-}{dx} = -\gamma_I \frac{|c_+|^2}{|c_+|^2+|c_-|^2} \tag{10}$$

A conservation relation for the intensities of the two waves can be derived from Eqs.(7) and (8), resulting in,

This conservation allows the determination of the evolution of the wave intensities in a closed form. The results are:

$$\frac{d}{dx}[|c_+|^2-|c_-|^2] = 0 \quad or \quad |c_+|^2-|c_-|^2 = 2C_0 \tag{11}$$

$$|c_+|^2 = C_0+\sqrt{C_0+B_0^2e^{2\gamma_R x}}, \tag{12}$$

$$|c_-|^2 = -C_0+\sqrt{C_0+ B_0^2e^{2\gamma_R x}}, \tag{13}$$

Where C_0 and B_0 are constants of integration to be determined by boundary conditions. The evolution of the phases of the two waves can also be determined analytically as follows:

$$\varphi_+=\frac{1}{2\gamma_R}\ln[(\frac{C_0}{B_0})+\sqrt{e^{2\gamma_R x}+(\frac{C_0}{B_0})^2}]+\frac{\gamma_I}{2}x + E_0 , \tag{14}$$

$$\varphi_- = \varphi_+ - \gamma_I\,\chi - D_0 , \tag{15}$$

Again, E_0 and D_0 are constants of integration to be determined by boundary conditions.

The boundary conditions associated with Maxwell's equations require that the tangential components of the electric and magnetic field be continuous at the interfaces at $x=0$ and $x=-a$. For the cover-PR interface at $x=0$, the boundary conditions are:

$$a_i + b_r = C_-(0) + C_+(0) \tag{16}$$

$$-ik_{x1}(a_i-b_r) = [-ik_{x2}C_-(0) + \frac{dC_-}{dx}|_{x=0}] + [ik_{x2}C_-(0) + \frac{dC_-}{dx}|_{x=0}] \tag{17}$$

Using the expressions for the intensities and phase of the waves given by Eqs (12)-(15), the boundary conditions, Eqs(16)-(17) are equivalent to:

$$-ik_{x1}a_i=\left[-i(k_{x1}+k_{x2})+\gamma^*\frac{C_0+(C_0^2+B_0^2)^{\frac{1}{2}}}{2(C_0^2+B_0^2)}\right]\sqrt{-C_0+(C_0^2+B^{2_0})^{\frac{1}{2}}}\; e^{i(E_0-D_0)}$$
$$+\left[-i\,(-k_{x1}+k_{x2})+\frac{-C_0+(C_0^2+B_0^2)^{\frac{1}{2}}}{2\,(C_0^2+B_0^2)^{\frac{1}{2}}}\right]\sqrt{C_0+(C_0^2+B_0^2)^{\frac{1}{2}}}\; e^{iB_0} \tag{18}$$

For the PR-substrate interface at $x= -a$, the boundary conditions are:

$$a_i = C_-(-a)e^{ik_{x2}a} + C_+(-a)\,e^{-ik_{x2}a}, \tag{19}$$

$$-ik_{x3}a_i=\left[-ik_{x2}C_-(-a)+\frac{dC_-}{dx}\Big|_{x=0}\right]e^{ik_{x2}a}+\left[ik_{x2}C_-(-a)+\frac{dC_-}{dx}\Big|_{a}\right]e^{-ik_{x2}a} \tag{20}$$

Again , using the expressions for the intensities and phases of the waves, the boundary conditions Eqs.(19) and (20) are equivalent to:

$$\left[-i(k_{x2}-k_{x3})+\gamma^*\frac{C_0+(C_0^2+B_0^2e^{-2\gamma_R a})^{\frac{1}{2}}}{2(C_0^2+B_0^2e^{-2\gamma_R a})^{\frac{1}{2}}}\right]\sqrt{-C_0+(C_0^2+B_0^2e^{-2\gamma_R a})^{\frac{1}{2}}}\; e^{i(k_{x2}a+\gamma_i a-D_0)}$$
$$+\left[i(k_{x2}+k_{x3})+\gamma\frac{-C_0+(C_0^2+B_0^2e^{2\gamma_R a})^{\frac{1}{2}}}{2(C_0^2+B^{2_0}e^{-2\gamma_R a})^{\frac{1}{2}}}\right]\sqrt{C_0+(C_0^2+B_0^2e^{-2\gamma_R a})^{\frac{1}{2}}}\; e^{-ik_{x3}a}=0 \tag{21}$$

For the present device, no DC electric field is applied to the PR film and hence the two-wave coupling coefficient is real. The boundary conditions Eqs. (18) and (21) , (both complex) can be transformed into four real equations. From Eq.(18) ,we obtain for the real and imaginary part:

$$-2k_{x1}a_i\sin E_0=[\gamma\frac{C_0+(C_0^2+B_0^2)^{\frac{1}{2}}}{2(C_0^2+B_0^2)^{\frac{1}{2}}}\cos D_0+(k_{x1}+k_{x2})\sin D_0][-C_0+(C_0^2+B_0^2)^{\frac{1}{2}}]^{\frac{1}{2}}$$

$$+\gamma\frac{C_0+(C_0+B_0)^{\frac{1}{2}}[-C_0+(C_0+B_0)^{\frac{1}{2}}]^{\frac{1}{2}}}{2(C_0+B_0^{)^{\frac{1}{2}}}} \tag{22}$$

$$-2k_{x1}a_i\cos E_0=-[\gamma\frac{C_0+(C_0^2+B_0^2)^{\frac{1}{2}}}{2(C_0^2+B_0^2)^{\frac{1}{2}}}\sin D_0+(k_{x1}+k_{x2})\cos D_0][-C_0+(C_0^2+B_0^2)^{\frac{1}{2}}]^{\frac{1}{2}} \tag{23}$$

$$+i(k_{x2}-k_{x1})[-C_0+(C_0^2+B_0^2)^{\frac{1}{2}}]^{\frac{1}{2}}$$

From Eq.(21), we obtain for the magnitude and phase:

$$4k_{x2}k_{x3}(C_0^2+B_0^2e^{-2\gamma_R a})^{\frac{1}{2}}+2(k_{x2}^2+k_{x3}^2)C_0-\frac{\gamma^2B_0^2e^{-2\gamma_R a}}{2(C_0^2+B_0^2e^{-2\gamma_R a})}C_0=0 \tag{24}$$

$$D_0=2K_{x2}a+\pi-\arctan\{\frac{2(k_{x2}-k_{x3})(C_0^2+B_0^2e^{-2\gamma_R a})^{\frac{1}{2}}}{\gamma[C_0+(C_0^2+B_0^2e^{-2\gamma_R a})^{\frac{1}{2}}]}\}$$

$$-\arctan\{\frac{2(k_{x2}-k_{x3})(C_0+B_0^2e^{-2\gamma_R a})^{\frac{2}{2}}}{[-C_0+(C_0^2+B_0^2e^{\gamma_R a})^{\frac{1}{2}}]}\} \tag{25}$$

We recognize that Eq.(24) can be expressed as an algebraic equation for the ratio $X=(C_0/B_0)^2$ as the single unknown. Let $g = exp(-2\gamma a)$, we obtain a third-order polynomial equation for:

$X = (C_0/B_0)^2$ *as:*

$$A_1X^3 + A_2X^2 + A_3X + A_4 = 0 \quad (26)$$

Where,

$$A_1 = 4(k_{x2}^2 - k_{x3}^2)^2, \quad (26a)$$

$$A_2 = g\,[4\,k_{x2}^2 + k_{x3}^4 - 32\,k_{x2}^2\,k_{x2}^3 - 2\gamma^2\,(k_{x2}^2 + k_{x3}^2)], \quad (26b)$$

$$A_3 = g^2\,[4\,k_{x2}^4 + k_{x3}^4 - 40\,k_{x2}^2\,k_{x32} - 2\gamma^2\,(k_{x2}^2 + k_{x3}^2 + \gamma^4/4)], \quad (26c)$$

and

$$A_4 = -16k_{x2}^2\,k_{x3}^2\,g^3, \quad (26d)$$

Since the cubic algebraic Eq.(26) can be solved analytically, we essentially solved the nonlinear problem analytically. Once the ratio $X=(C_0/B_0)^2$ is known, D_0 can be obtained from Eq.(25), B_0 can be obtained from Eqs.(22) and (23) using $\sin^2E_0 + \cos^2E_0 = 1$. Subsequently E_0 and C_0 can be determined from $X=(C_0/B_0)^2$ and Eqs.(22)and (23). There is a one-to-one correspondence between $X=(C_0/B_0)$ and E_0, D_0, and C_0. Therefore in order to have optical bistability, multiple values of $X=(C_0/B_0)^2$ should be allowed (three values, two of them are associated with stable equilibria and one associated with an unstable equilibrium.)

The necessary conditions for the above equation to have three real and positive solutions for $X=(C_0/B_0)^2$ is as follows:

$$\frac{A_2}{A_1}<0, \quad \frac{A_3}{A_1}>0, \quad \frac{A_4}{A_1}<0, \quad (27)$$

Since $A_1>0$, and $A_4<0$, $A_4/A_1<0$ is automatically satisfied. In order for $A_2<0$, and $A_3>0$, so that $A_2/A_1<0$ and $A_3/A_1>0$, it is necessary that

$$\gamma^4 > 32\,k_{x2}^3\,k_{x3}^2 \quad (28)$$

2.3 RESULTS AND DISCUSSIONS

The theoretical work has clearly demonstrated the feasibility of the proposed thin film photorefractive optical bistable device. The results are summarized as follow:

1) A general analytical solution for the proposed bistable device has been deduced (Eq. 26). It provides a powerful tool for designing and optimized device configurations for the Phase II program.

2) The theoretical work has also generated a set of necessary conditions (Eqs. 27-28) for photorefractive materials to be utilized in an optical bistable device.

3) Based on the above conditions, we have estimated the required doping concentrations of various photorefractive materials, especially, some II-VI semiconductors, *ZnTe:V, CdTe:V, CdS, CdMnTe* which are promising IR photorefractive materials. Brimrose is the leader in research and commercially production of these materials.

   For a photorefractive material to be utilized in the bistable device, it must satisfy Eq. 28. The two-wave mixing coefficient (γ) is on the order of 10^4 at best [18], even for highly efficient photorefractive crystals such as $BaTiO_3$. While $k_{x2,3} = (2\pi n/\lambda_0) \cos\theta_{2,3}$ is in general greater than 10^4 where $\theta_{2,3}$ is the direction of the plane wave in the film and the substrate with respect to the normal to the interface. Even though with $(2\pi n/\lambda_0) \approx 2x10^7$ one may propose to chose $\theta_{2,3} \approx 90^0$ to satisfy Eq.(28), this would result in a very large device length. Through the theoretical calculation, it is suggested that for making the proposed bistable device, the mid-gap electronic trap concentration in the photorefractive materials should be at order of 10^{19} to $10^{20}/cm^3$. At the present time, Brimrose's photorefractive semiconductors have a strong dopant concentration of 10^{19} to $10^{20}/cm^3$. However, due to the defect nature causing point defect variance within the stoichiometric range, the effective electronic trap concentrations in these materials are of the order of 10^{14} to $10^{15}/cm^3$. Therefore, there is nc semiconductor material which is suitable for this particular device configuration and further material developments are required.

4. The semiconductor photorefractive material with high electronic trap concentration will be researched and developed during the Phase II program for the proposed bistable device configuration.

3.0 A NOVEL OPTIC BISTABLE DEVICE USING SELF-PUMPED PHASE CONJUGATION IN PHOTOREFRACTIVE CRYSTAL KNSBN:Cu

3.1 DEVICE PRINCIPLE AND CONFIGURATION

The second optical bistable device studied in this work also utilizes the photorefractive nonlinearity as the nonlinear mechanism. The feedback is derived from a beam loop formed by two internal reflections at the adjacent crystal faces which is similar to the one in Feinberg's cat self-pumped phase conjugation experiment [16]. Figure 2 is the schematic illustration of the beam loop and interaction inside the crystal.

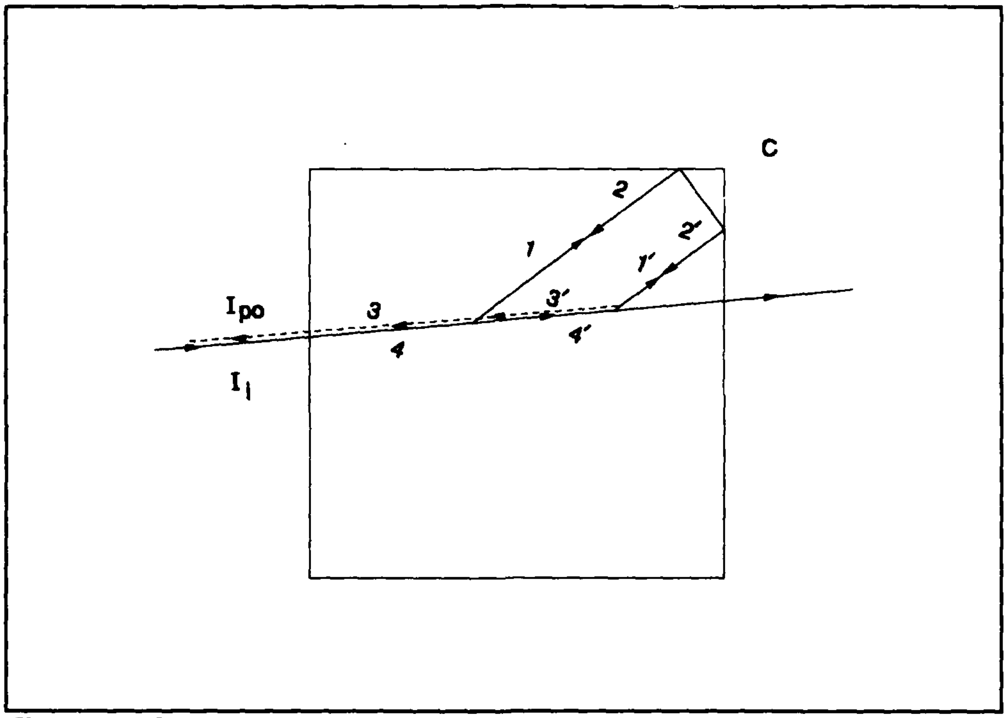

Figure 2 Schematic illustration of a bistable device using self-pumped phase conjugation in a KNSBN:Cu crystal.

As shown in the figure, due to the photorefractive effect, the incident beam I_i (beam 4 and 4') suffers an asymmetric self-defocusing and creates a fan of light that illuminates the edges of the crystal. The fan actually collapses into at least two narrow beams, 1 and 1'. These edges act as a two-dimensional corner-cube reflector and, by two internal reflections, directs the fan of light back toward the incident beam. It is speculated that each beam is composed of a pair of counter propagating beams, 2 and 2', so there are two counter propagating loops of light in the crystal C. Each pair of counter propagating beams mix with the incident beams 4 and 4' creating a phase conjugate output I_{po} (beams

3 and 3') by four-wave mixing. The phase conjugate beams 3 and 3' leaves the crystal C exactly along the direction of the incident beam I_i. Note that beams 3 and 3' can also act as pumping beams and create gain for the loop beams, which then creates gain for the conjugate pair (3 and 3'), therefore the process is bootstraped.

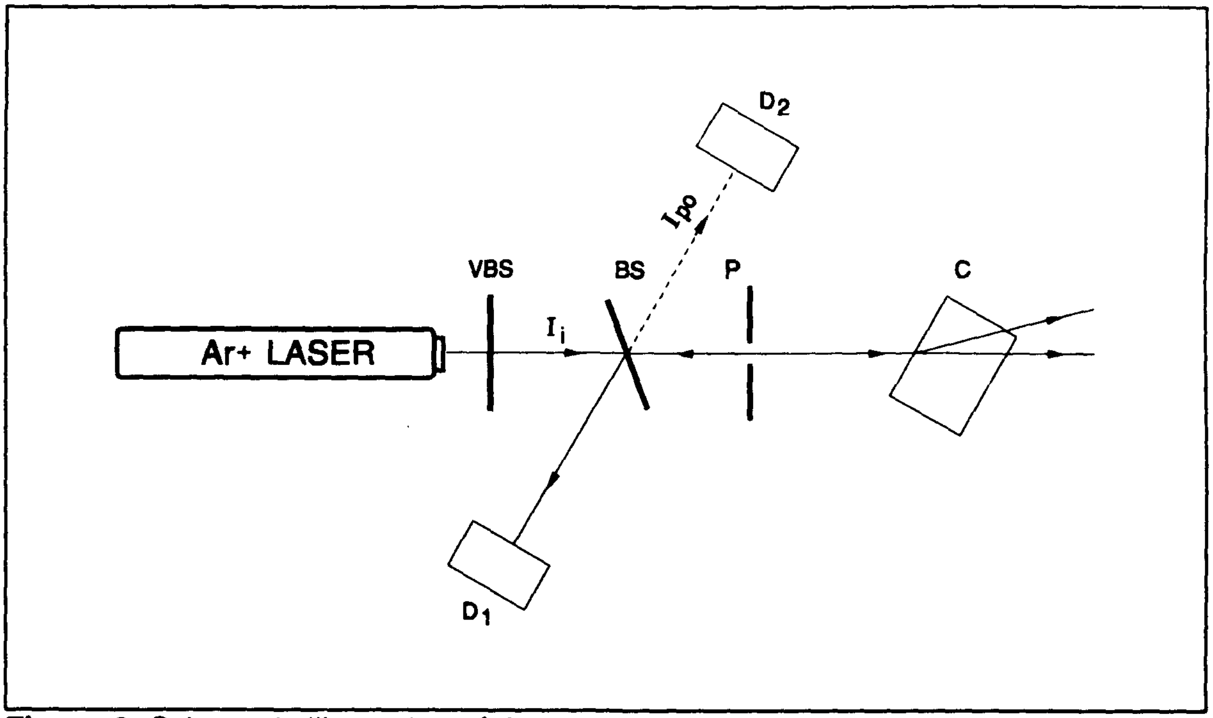

Figure 3. Schematic illustration of the experimental setup.

3.2 EXPERIMENTAL SETUP

Figure 3 is the schematic illustration of the experimental setup. In the experiment, a 6x6x6 mm single-domain electrically-poled photorefractive KNSBN:Cu crystal is used as the nonlinear medium. The output from a single-mode argon ion laser at 488 nm polarized parallel to the C-axis of the crystal is used as the light source. A variable beam splitter (VBS) is used to change the total incident intensity into the crystal. A fixed beam splitter (BS) splits the beam and allows the monitoring of the intensity of light incident onto the crystal by measuring the light intensity at the detector D_1. The argon laser light is incident, through a pinhole (P) upon the crystal C at an incident angle of about 50 degrees with respect to the normal of the crystal surface. The pinhole is merely used to block light reflected from the crystal surface. Crystal C is mounted on a precision rotation stage fixed to a XYZ translation stage to allow adjustment of the incident angle and location of the incident light. For a few particular incident angles and locations of incidence, self-pumped phase conjugation occurs. After a transient period, a stable phase conjugate beam appears at the detector D_2. We measured the input (I_i) and output

(I_{po}) relations and observed optical bistability in this simple experimental setup.

Figure 4 is photograph which shows the beam fanning and the beam path loop in the KNSBN:Cu crystal. Figure 5 is the photograph of showing the spot of the transmitted beam through the crystal.

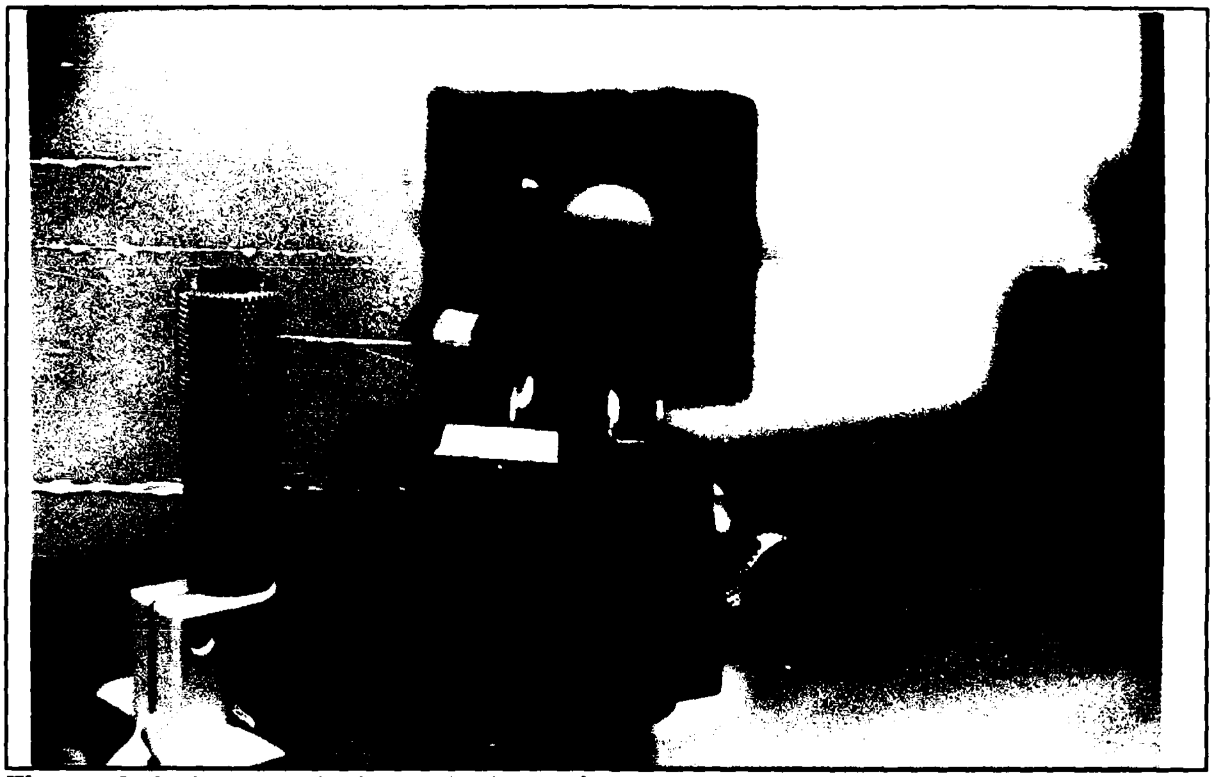

Figure 4. A photograph shows the beam fanning and the beam path loop in the crystal.

3.3 EXPERIMENTAL RESULTS

The output power of the argon ion laser is 150 mW. The intensity of incident beam Ii is gradually changed by rotating the variable beam splitter. The maximum and minimum intensities of I_i are 40 mW and 1 mW, respectively. Within this intensity range on the order of mW/mm^2 optical bistability was achieved.

We first present the nonmonotonic relationship between the phase conjugation reflectivity and the output power in Figure 6. The phase conjugation reflectivity initially increases when the output power is increased from about 2 mW. At an output power is increased to about 10 mW, the phase conjugation reflectivity levels off, until an output power of 20

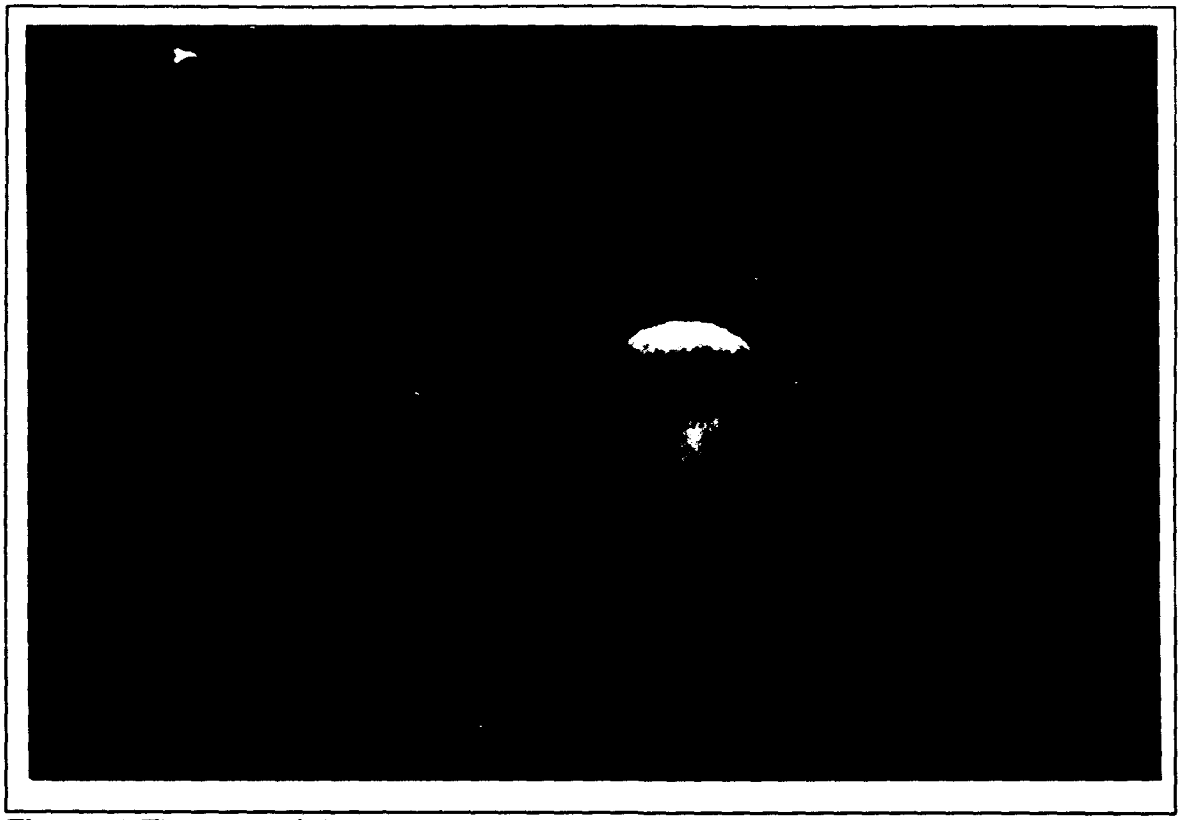

Figure 5 The spot of the transmitted beam through the crystal.

W. When the output power is increased beyond 20 mW, the phase conjugation reflectivity starts to decrease with increased output power. This nonmonotonic relationship between the output power and the phase conjugation reflectivity ensures the occurrence of optical bistability. The bistable operation is described next.
The bistable operation in the self-pumped phase conjugator is illustrated in Figure 7. The output power is plotted against the input power as the incident power is modulated. When the incident power is increased from 14 mW to 38 mW, the output vs input power follows the lower trace in Figure 7; while when the incident power is decrease from 38 mW to 14 mW, the output vs input power follows the upper trace. The upward and downward traces form the bistable hysteresis loop. It is apparent that with a fixed input power between 20 mW and 34 mW, there are two states (bistable) of the output power, dependent upon the history of the input power. The bistability threshold intensity of 650 mW/cm^2 is, to the best of our knowledge, the lowest in all the bistable devices demonstrated so far.

In summary, a bulk version of the low threshold optical bistable device was experimentally demonstrated. The threshold for the bistable operation is the lowest of its kind demonstrated so far. The result will be submitted for publication in *Photonics Lett.*

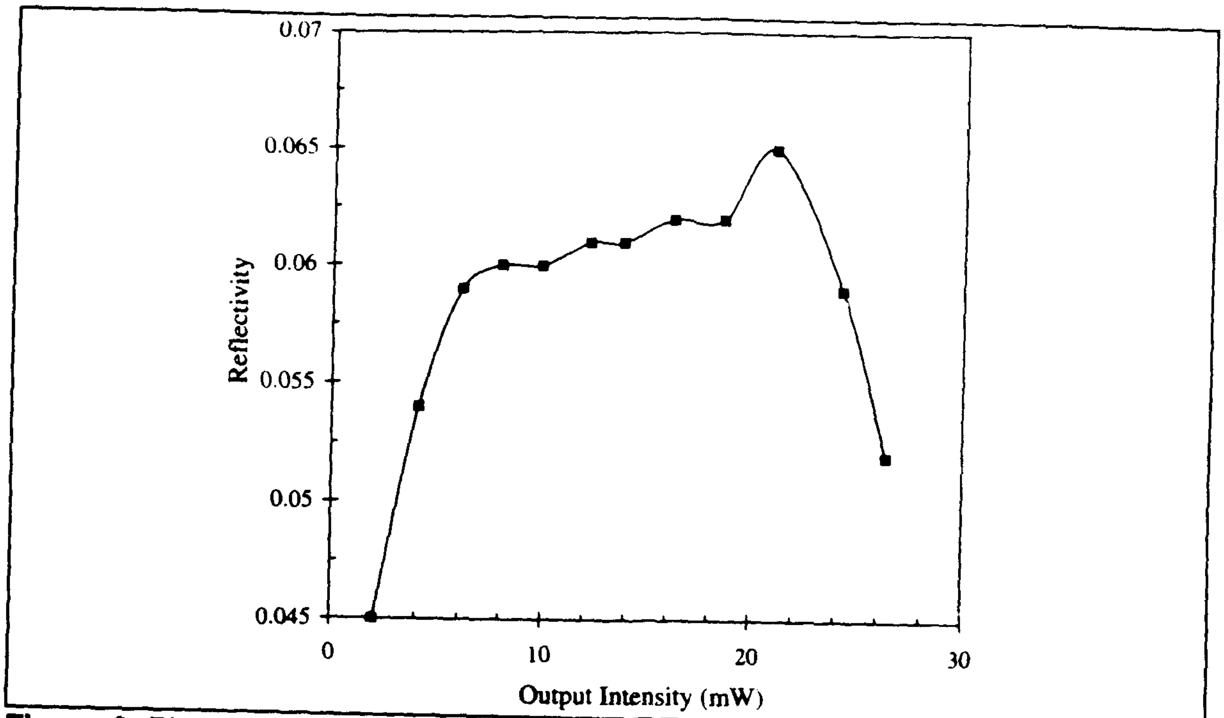

Figure 6. Phase conjugation reflectivity versus output intensity.

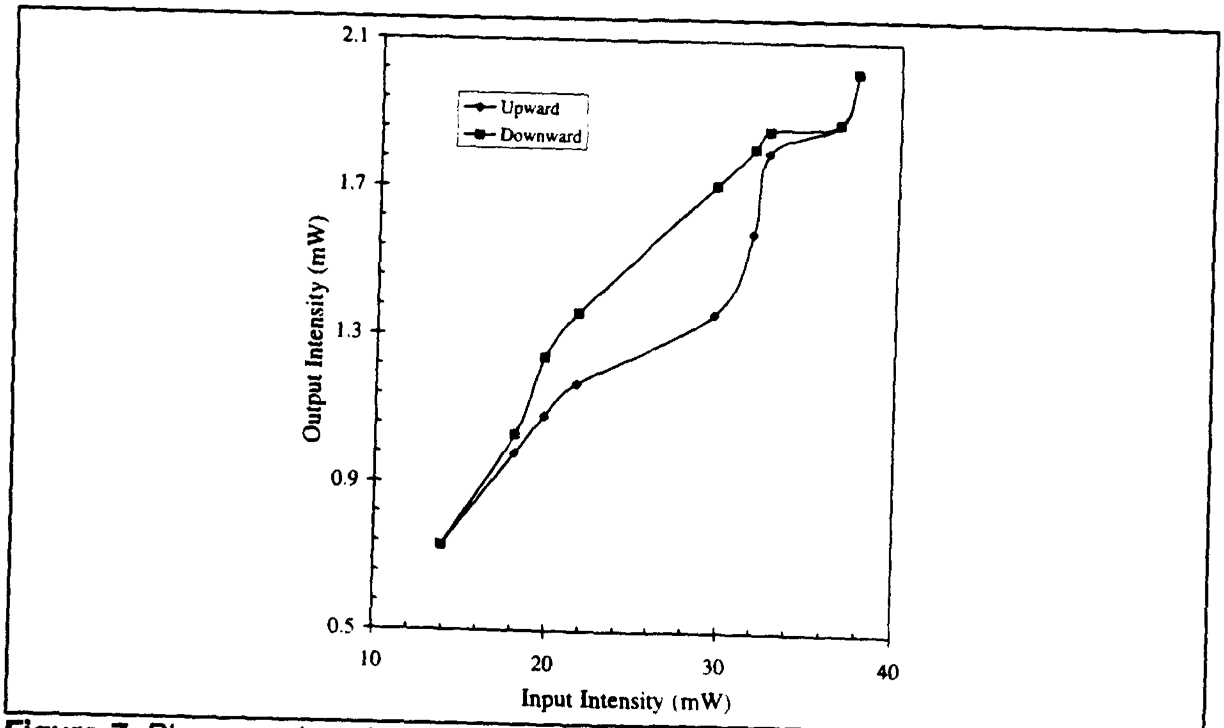

Figure 7. Phase conjugation output I_{po} versus input I_i - Hysteresis loop.

4.0 POTENTIAL APPLICATIONS

This research work has resulted in significant progress in the area of optical bistability. The developed low threshold intensity optical bistable devices can be used in various applications. They include all-optic bridges/routers for LANs and WANs, high-density storage devices for multi-media and video on-demand, as essential building blocks for any kind of optical digital computing and signal processing systems, etc..

5.0 CONCLUSIONS AND PHASE II PROGRAM

In summary, we have successfully completed the proposed SBIR Phase I objective, research and development in low-threshold intensity optical bistable devices using photorefractive nonlinearity. A thin photorefractive film optical bistable device was proposed in the Phase I proposal. The feasibility of this device was theoretically investigated. The theoretical feasibility study formulates the materials requirements in such a kind of configuration for Phase II research. Also, we have proposed and investigated another configuration of an optical bistable device that does not require advanced photorefractive material, namely, the KNSBN:Cu self-pumped phase conjugator. We have experimentally demonstrated a successful low-threshold optical bistable operation. To the best of our knowledge, the threshold of 650 mW/cm^2 is the lowest of its kind to be achieved so far.

In the Phase II program, emphasis will be placed in following areas:

Device Optimization. Based upon the results from Phase I, further work for optimal parameters of the bistable device using self-pumped phase conjugation and two wave mixing in bulk crystals. The device will also be implemented in Brimrose's II-VI semiconductor materials which have faster response time and operate in IR wavelengths. In addition, the proposed thin film device will also be further optimized for achieving a better performance.

Photorefractive Materials Growth. The on going research in photorefractive materials growth in phase II work will be aimed at increasing the deep trap level concentration in photorefractive II-VI semiconductors which are preferred due to their fast response time and matched with the wavelengths of laser diodes.

There are anticipated **commercial spin-offs** during the Phase II program. Novel optical bistable devices and subsystems will be available for commercial sales for applications ranging from optical computing, high-density all-optical memory for video on demand, optical communications, etc.

6.0 REFERENCE

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